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QUANTITATIVE FRACTURE PROPERTIES IN THE TRANSITION REGION AND NEAR TRANSITION REGION FOR THIN PLATE SHIP STEEL

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FACTS Engineering Inc.

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FOR THIN PLATE SHIP STEEL

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ABSTRACT

Accurate characterization of mechanical materials properties is integral to the development of marine platform designs, which will exhibit acceptable levels of damage tolerance under extreme service conditions. A study has been performed to evaluate several laboratory test procedures for the characterization of fracture toughness in the ductile to brittle transition region. Test procedures evaluated include ASTM E-604, ASTM E-813, and strain energy density generated from uniaxial tension specimens. Marine structural steels and weldments used in the evaluation include CSA G40.21 350WT, CSA G40.21 38WT, and ASTM A-517.

A comparison of transition curves generated from pressed-notch ASTM E-604 specimens and fatigue precracked specimens indicates that the pressed-notch specimen geometry provides an acceptable approximation of structural transition. The addition of side grooves to E-604 specimens produced out of plane crack propagation resulting in significant scatter in the transition curve results.

Elastic and elastic-plastic fracture toughness tests conducted on 350WT plate specimens revealed limit load tearing in the L-T crack plane orientation and J-controlled crack extension in the T-L orientations. CSA G40.21 350WT weldments tested generated inconsistent results ranging from initiation of a brittle instability at -30°C to limit load tearing at -50°C. ASTM A-517 welds generally exhibited J-controlled crack extensions with "pop-ins" evident in the load-displacement records.

A customized uniaxial tension extensometer was developed for tracking deflections at multiple points along the gauge of a tension specimen. Accuracy of the extensometer was verified through the prediction of the average cross sectional area of the specimen over the minimum interval between measurement points adjacent to the fracture plane. The test results indicate a decrease in the strain energy density capacity of CSA G40.21 38WT as the temperature is lowered from 22°C to -20°C.

RÉSUMÉ

La caractérisation précise des propriétés mécaniques des matériaux fait partie intégrante de l'élaboration des conceptions de plates-formes maritimes qui présenteront des degrés acceptables de tolérance aux dommages dans des conditions de service extrêmes. Une étude a été menée afin d'évaluer plusieurs procédures d'essai en laboratoire visant la caractérisation de la ténacité à la rupture dans la zone de transition de la ductilité à la fragilité. Les procédures d'essai évaluées comprennent les méthodes E-604 et E-813 de l'ASTM et la densité de l'énergie des contraintes générées par les éprouvettes soumises à une traction uniaxiale. Les aciers de construction marins et les assemblages soudés utilisés dans l'évaluation comprennent les types 350WT, 38WT de la norme CSA G40.21 et A-517 de l'ASTM.

Une comparaison des courbes de transition générées par les éprouvettes entaillées à la presse selon la méthode E-604 de l'ASTM et par les éprouvettes préfissurées par la fatigue indique que la géométrie des éprouvettes entaillées à la presse fournit une approximation acceptable de la transition structurale. L'ajout de rainures latérales aux éprouvettes de la méthode E-604 entraîne une propagation des fissures hors plan résultant en une dispersion significative des résultats des courbes de transition.

Des essais de ténacité à la rupture élastique et élastique-plastique menés sur des éprouvettes de plaques du type 350WT ont mis en évidence un déchirement à la charge limite dans l'orientation du plan des fissures L-T et un prolongement des fissures avec contrôle de J dans les orientations T-L. Les assemblages soudés du type 350WT de la norme CSA G40.21 mis à l'essai produisent des résultats irréguliers variant du commencement d'instabilité de fragilisation à -30 °C au déchirement à la charge limite à -50 °C. Les soudures de la méthode A-517 de l'ASTM présentent généralement des prolongements de fissures avec contrôle de J avec des pop-ins » évidents dans les données de déplacement de la charge.

Un extensomètre à traction uniaxiale a été développé spécialement pour mesurer les flèches à des points multiples le long de l'épaisseur d'une éprouvette soumise à une traction. La précision de l'extensomètre a été vérifiée par la prédiction de la surface moyenne de la section de l'éprouvette sur l'intervalle minimal entre les points de mesure contigus au plan de fracture. Les résultats des essais indiquent une diminution de la capacité de densité de l'énergie de contrainte de la plaque 38WT de la norme CSA G40.21 lorsque la température est abaissée de 22 °C à -20 °C.

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1.0 INTRODUCTION

In the past five to ten years, the commercial shipping industry has recorded an increase in structural fracture failures. This increase has led to the development of knowledge pertaining to the fracture mechanisms relevant to the ductile to brittle transition region. To some extent, the increase in failure incidents can be attributed to a combination of longer periods between scheduled maintenance and the absence of a rigorous damage tolerance assessment of the construction materials during the design stage of these structures.

Recently, the Canadian Navy added twelve "Halifax Class" patrol frigates (CPF) to its fleet. The global design stresses in these structures under operational service conditions were increased over previous military designs. Also, in an effort to reduce life-cycle maintenance costs, fleet maintenance facilities are implementing dockside inspection and maintenance to increase the periods between the more rigorous refit maintenance cycles. Responding to these changes, the defence research and development community has initiated both in-house and contracted programs to ensure that these structures maintain an acceptable level of damage tolerance for the assigned operational envelop.

Accurate characterization of mechanical material properties is integral to the development of marine platform designs which will exhibit acceptable levels of damage tolerance under extreme service conditions. Currently, structural steels and welds comprise the bulk of materials used to fabricate marine platforms. Fracture mechanics is a mechanical/materials discipline which evolved to provide designers with information critical to the longevity and safe service performance of structures which contain defects. It is the study of the interaction between defects, applied stress, geometry, and materials properties. Defects can be formed during the material processing stage (rolling laminations), during fabrication of the structure (weld defects) or formed as a result of the in service stresses and strains applied to the structure (fatigue cracking). Cracks will continue to grow by subcritical mechanisms until they reach a critical length at which point they will initiate and propagate. These cracks can propagate under limit state conditions either by ductile tearing, where the mechanism is dominated by microvoid coalescence, or by brittle propagation, which is dominated by transgranular cleavage. Which mechanism dominates is determined by variables such as temperature, strain rate, and defect constraint.

The study detailed in this report focuses on evaluating several laboratory test procedures for the generation of fracture toughness information in the ductile to brittle transition region. Materials used in this experimental program are consistent with those used to fabricate and maintain Canadian military marine platforms. Both material and test procedure information generated during this program will be assessed with respect to their structural significance.

2.0 BACKGROUND

The key to small scale testing is to provide test results which are transferable to larger structures. Testing procedures for analysing the transition properties of steels and weldments can be divided into two broad categories, namely, qualitative and quantitative procedures.

2.1 Qualitative Test Procedures

Several test procedures have been incorporated into standardized test methods for the development of temperature transition curves. The most commonly used procedure is ASTM E-23 [1], which is commonly referred to as the Charpy V-notch test method. The Charpy V-notch is a dynamic test which uses a 10 mm x 10 mm x 55 mm bend bar with a shallow 2 mm machined notch. The root tip radius of this notch is 0.25 mm. The energy required to fracture the specimens is recorded for various temperatures. This data is used to generate a temperature transition curve.

The dynamic tear test developed by US naval researchers was standardized into ASTM E-604 [2]. The E-604 specimen is significantly larger than the E-23 specimen (16 mm x 40.62 mm x 181mm) providing increased lateral and back face constraint as compared to the E-23 specimen. The 12 mm notch in this specimen is pressed with a hardened knife to increase the crack tip stress intensity factor. Similar to the E-23 test method, the fracture energy required to fail the specimen at various temperatures is used as the data for developing the material transition curve.

Drop-weight tear testing of ferritic steels (ASTM E-436 [3]) provides a visual method for determining the transition behaviour of materials. A 75 mm x 300 mm specimen of the as received thickness of the plate is impacted at dynamic loading rates. A shallow pressed-notch is created on the tension surface to initiate the fracture event. The standard uses the percent area of cleavage fracture to determine the transition characteristics of a material.

The specimen configuration of the nil ductility test method (ASTM E-208 [4]) is substantially different than the above described test methods. The specimen thickness to height of this specimen is 3.5/1 (in all the above procedures, the thickness to height is less than 1/1). This specimen incorporates a brittle starter notch to initiate the fracture. As opposed to getting a complete transition curve, this test method is used to define the nil ductility temperature (NDT) at which complete lateral cracking occurs across the specimen.

A relatively recent unstandardized test procedure for the generation of transition curves is the measurement of the residual shear lip created by the fracture process [5,6]. The specimen geometry used is the same as in ASTM E-604. Numerous studies have shown that the shear lip width correlates well to fracture energy. Intuitively, shear lip width should also correlate well with crack arrest toughness, K_{ar} , since it is measured at a point on the fracture surface where a brittle crack is dominating the fracture process. This test has the added advantage that it does not require the expensive instrumentation of tests such as E-604.

The test procedures described above produce transition curves which may be significantly different. A significant temperature shift can occur when comparing DT energy and shear lip transition curves to Charpy V-notch transition curves [7]. The lower transition temperature generated by Charpy V-notch specimens is attributed to the lack of specimen capacity owing to specimen size and notch acuity differences [7]. The current program focuses on the ability of the dynamic tear (E-604) specimen geometry with a pressed-notch to accurately predict structural performance. Dynamic tear transition curves will be compared to transition curves generated from fatigue precracked specimens and also to specimens (both pressed-notch and fatigue precracked) where the lateral constraint has been altered by side-grooving the specimens.

2.2 Quantitative Test Procedures

Several crack tip parameters have been developed to characterize the initiation and propagation of cracks. Linear-elastic parameters include K integral and elastic-plastic parameters include J integral. ASTM has developed and published standards for the measurement of these parameters under quasistatic conditions (E-399 and E-1737).

Fracture parameters such as K and J are derived by analysing the two dimensional stress/strain fields in the vicinity of a crack tip. The validity of these parameters is predicated on the assumption that the variation in lateral constraint through the thickness of the specimen remains relatively constant across the majority of the crack front. While these parameters may provide acceptable approximations in specimens where these lateral and back face constraint conditions are satisfied, the development of shear lips (tunnelling cracks) in tough thin plate material in and around the structural transition temperature often invalidates the crack growth crack front straightness criteria published in elastic-plastic standards. One approach to increase the crack front straightness (i.e. reduce the variation in through thickness constraint) has been to side groove specimens. While this approach has been shown to improve crack front straightness, it limits the utility of the subsequent engineering value generated by the test. The current study will evaluate the fracture toughness of several CPF structural steels and welds using the test procedure and validity criteria in accordance with ASTM E-399 and ASTM E-813.

For thin plate material in or near the structural transition, where accumulated lateral strains are important, a volumetric approach may provide a more accurate approximation of material fracture toughness. Strain energy density, which is defined as the strain energy per unit of volume, is an approach where the contributions generated by lateral (through thickness) strains are included in the calculated values of critical strain energy density. The majority of research being conducted is focused on developing complex analytical algorithms for deriving critical strain energy density values from detailed knowledge of the material constitutive properties.

A common experimental test used to describe the constitutive flow properties of metallic materials is the uniaxial tension test (ASTM E-08). Specimens with a uniform gauge length are fixed between suitable grips and deflected under displacement control using a feedback sensor

placed remote from the specimen. A load transducer placed remote to the specimen and an instrumented two point extensometer attached directly onto the surface of the specimen (spanning a substantial portion of the gauge length) monitors load and total deflection of the gauge length, respectively. Typical load-deflection data generated during uniaxial tension tests is shown in Figure 1.

During the test, specimen reaction to the applied deflection can be categorized into three distinct behaviours; Zone 1, Zone 2, and Zone 3. In Zone 1, the relationship between stress and strain is governed by the elastic properties of the material. As the applied stress is increased beyond the material yield point (Zone 2), the uniform section of the gauge length sustains a non-recoverable plastic component to the applied deflection. The load bearing capacity of the specimen continues to increase owing to the strain hardening mechanisms. At the point where the increase in specimen load bearing capacity due to strain hardening is less than the decrease in load bearing capacity due to a cross section reduction owing to plasticity, the specimen begins to neck concentrating the plastic strain component. The necking process will continue to decrease the cross sectional area until, combined with stored elastic machine deflection, a ductile load instability precipitates.

There are several instrumentation problems associated with the conventional automated practices used to determine true stress-true strain. These problems will be listed separately for base plate and weldments.

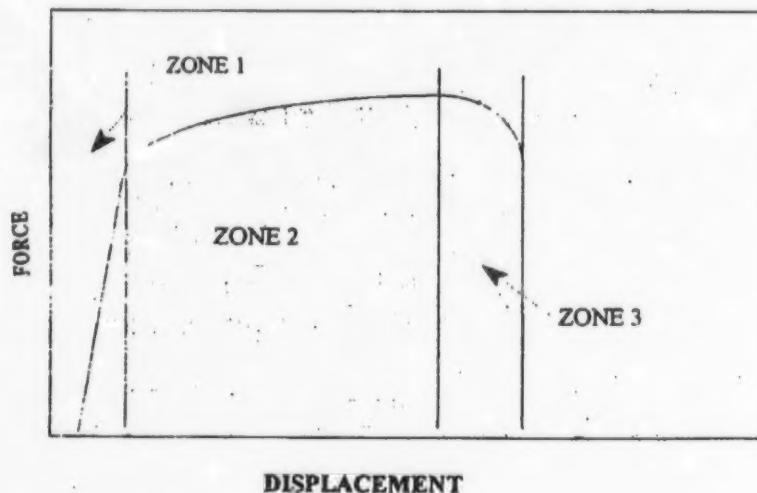


Figure 1 - Typical load/displacement data for a uniaxial tension test.

2.2.1 Base Plate

Again referring to Figure 1, a tensile test of a homogenous isotropic material consists of three stages; the elastic regime (Zone 1), the uniform stable plastic regime (Zone 2), and the plastic regime after the onset of necking (Zone 3). Measuring specimen gauge length deflections using the instrumentation procedure outlined in ASTM E-08 provides accurate true stress-true strain information up to the onset of localized necking. The extensometer data reflecting global changes to gauge length is very conservative after this point.

2.2.2 Weldment

A tensile test of a non-homogenous anisotropic material consists of three stages; the elastic regime, a non-uniform stable plastic regime, and the unstable plastic regime after the onset of necking. Thus, determining true stress-true strain for a weldment system suffers from all the problems described above for the plate material. In addition to those problems, the plastic strain is partitioned non-uniformly between the weldment and base plate over the specimen gauge length. If the weldment system of interest is over matched with respect to the base plate, averaging strain over the entire gauge length using conventional instrumentation techniques will provide non-conservative estimates of weld metal strain.

Studies performed at NRL [8] developed a hybrid experimental/analytical procedure for generating the true stress/true strain properties of homogenous materials. Several specimen geometries with varying L/D ratios (where L is the gauge length and D is the initial specimen diameter) were tested to failure. The resulting mechanical load deflection records were used as boundary condition input to an analytical model where the constitutive stress-strain relationship was the unknown. By correlating the resulting stress-strain data produced from the various specimen geometries, a material stress-strain relationship was developed.

Work conducted at DREA/DL [9] developed a procedure for generating the stress-strain relationship at various temperatures for predominately plane stress specimens. Prior to the onset of necking, the stress-strain relationship was developed from the instrumented load-deflection data. The rupture stress was determined from the specimen load at rupture and the final cross sectional area was calculated using the minimum specimen gauge diameter subsequent to testing. The rupture strain was determined from deflection changes observed on an etched grid adjacent to the rupture plane. The relationship between rupture and the onset of necking was assumed to be linear.

The focus of the current study is to develop an instrumented method of minimizing the errors associated with averaging localized events over the entire gauge length. This objective can be achieved by monitoring the specimen changes in length at several points over the gauge length. True stress-true strain are generated over each discrete interval. Because individual gauge lengths are significantly reduced over conventional instrumentation methods, errors introduced into localized strain events owing to gauge length averaging are minimized. Also, the stress-strain

relationship for the points adjacent to the rupture plane should provide an approximation of the critical strain energy density.

3.0 EXPERIMENTAL PROGRAM

3.1 ASTM E-604 Specimen Preparation

Eighty specimens were machined from 12.5 mm CSA G40.21 350WT material supplied by DREA/DL. Two sets of forty specimens each were fabricated from the plates such that the plate rolling direction with respect to the crack orientation conformed to the T-L and L-T orientations as specified in ASTM E-399. Twelve millimeter notches were machined into twenty specimens from each set of forty specimens. Ten specimens from each set of twenty specimens were side grooved to 20 percent of the specimen thickness. All forty specimens were subsequently pressed with a notch sharpening knife edge blade in accordance with ASTM E-604. The remaining forty specimens were machine notched to a depth of 18 mm. As with the pressed-notch specimens, side grooves of 20 percent of the thickness were machined into ten specimens each from the T-L and L-T orientations. The notches of these forty specimens were precompressed to 40 percent of the limit load as defined by ASTM E-1152 and subsequently fatigue precracked to a depth of approximately .55 a/W using an R ratio of 0.1 and a maximum stress intensity factor of 30 MPa/m.

3.2 ASTM E-604 Test Procedure

Specimens were tested at impact loading rates of approximately 5 m/s with a 275 kg crosshead. Prior to testing, specimens were conditioned to various temperatures ranging over the ductile-brittle transition of this material using a fluid cold bath. Analog impact signals generated from an instrumented tup were digitized using an 8 bit A/D converter and stored in a microprocessor for further analysis. Force-time information was converted into force displacement using conservation of energy principles for each specimen. Impact energy for each specimen was determined by integration of the force-displacement data. Shear lips produced on the non side-grooved specimens were measured subsequent to testing for comparison to the energy data.

3.3 ASTM E-813 Specimen Preparation

The specimens provided by DREA/DL were machined from five plates removed from HMCS Calgary for analysis. A listing of the specimens received, corresponding plate designations, and their respective test temperatures are given as:

<u>Plate Position Designation</u>	<u>DND ID</u>	<u>FACTS ID</u>	<u>Specimen Material</u>	<u>Test Temp°C</u>
1 Aft	C15	206	350WT weldment	-30
2 Aft	C24	208	A517 weldment	-50
	C25	203	A517 weldment	-30
3 Aft	C34	202	A517 weldment	-30
4 Aft	C44	207	350WT weldment	-30
	C45	209	350WT weldment	-50
5 Aft	C54	201	350WT Plate (L-T)	-30
	C55	204	350WT Plate (L-T)	-30
	C56	210	350WT Plate (L-T)	-50
	C510	211	350WT Plate (T-L)	-50
	C511	200	350WT Plate (T-L)	-30
	C512	205	350WT Plate (T-L)	-30

Received specimen dimensions were measured for compliance with ASTM E-604. Specimen thickness (B) was the as received thickness of the plate. To accommodate the clip gauge required for fatigue precracking, integral knife edges were machined into the lateral faces of the specimen notch at the lower surface of the specimen. Prior to testing, notch tips of the specimens were precompressed to 40 percent of the limit load as defined by ASTM E-1152 and subsequently fatigue precracked to a depth of approximately .55 a/W using an R ratio of 0.1 and a maximum stress intensity factor of 30 MPa/m.

3.4 ASTM E-813 Test Procedure

Specimens were tested at quasistatic loading rates using a fully automated servo-hydraulic materials test system. Prior to loading, each specimen was positioned on the three point bend fixture. Once the specimen was positioned, the control software applied a compressive pre-load to the specimen to fix it in place while the environmental chamber cooled the specimen to the desired test temperature. Specimens were soaked at the predetermined test temperature for a minimum of 15 minutes before the testing sequence was activated. The testing sequence was comprised of a monotonic loading rate of 0.05 mm/s. For the first ten cycles, the loading cycle was interrupted at 0.1 mm intervals for the unload/reload sequence required to obtain crack extension information. After the first ten cycles, the cycle interval was increased to 0.2 mm. Analog signals generated from an instrumented load cell, COD clip gauge, and remote ram LVDT were digitized using a 14 bit A/D converter and stored in a microprocessor for further analysis.

3.5 Strain Energy Density Instrumentation Development and Specimen Preparation

In order to measure differential strain for multiple intervals over the gauge length, a customized deflection sensor was developed. Figure 2 schematically represents the principle of operation for the deflection gauge designed. As shown in the schematic, the body of the deflection gauges are rigidly fixed to the tension specimen outside the gauge length of the specimen. The core of each gauge is fixed at one of nine evenly spaced intervals over the length of the gauge. During the test, individual gauges measure the absolute deflection with respect to the reference plane. Relative gauge length extension data can be calculated as the arithmetic difference in absolute deflection between any two gauge attachment points. Figure 3 shows the deflection gauge attached to the specimen prior to testing.

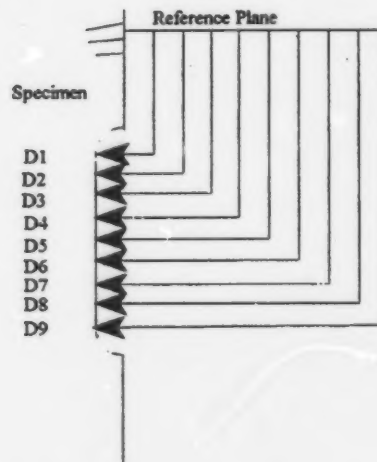


Figure 2 - Schematic representation of multi-point displacement gauge.

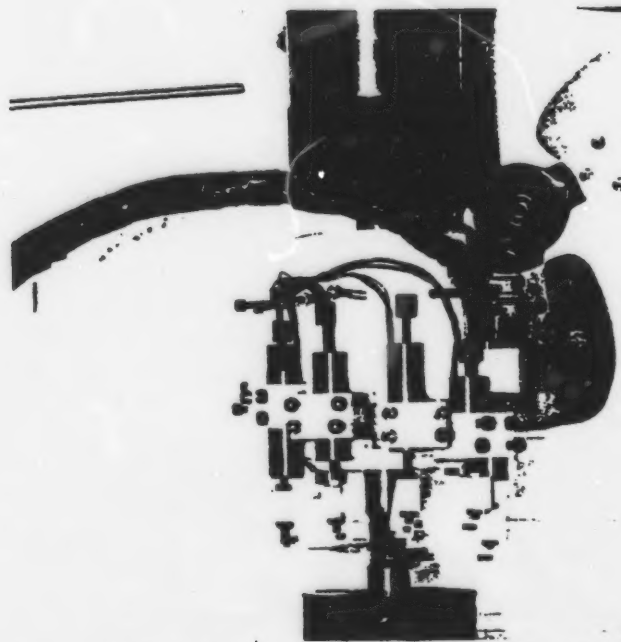


Figure 3 - Photograph of tension specimen with customized multi-point deflection sensor attached.

Three tension specimens were machined from a plate of CSA G40.21 38WT. The design of the specimens had two requirements; firstly, that the gauge length be sufficient to generate a fully developed plastic zone, and, secondly, that the length of the upper grip section be sufficient to attach the deflection gauge. Previous studies [8] indicate that specimens with an L/D ratio of 1 or greater generate fully developed plastic zones. The current specimen was, therefore, designed with a gauge diameter of 18.83 mm and a gauge length of 20.30 mm ($L/D = 1.08$). In order to incorporate the customized deflection gauges, the length of upper grip section was 230 mm, including 35 mm of attachment thread. The length of the lower grip section was 70 mm, including 35 mm of attachment thread.

3.6 Strain Energy Density Test Procedure

Prior to loading, each end of the specimen was threaded into the load train via self centring grips. Nine linear variable displacement transducers (LVDT) were attached such that adjacent LVDTs maintained approximately 2.5 mm longitudinal and 40° of rotational spacing along the specimen gauge length. Specimens were also etched with copper sulphate and scribed circumferentially at the gauge attachment points to provide a visual check on the accuracy of the displacement sensors. To minimize slippage of the displacement sensors during the test, attachment points consisted of socketing a pointed hardened steel rod into a punch set on the surface of the specimen. Once the specimen sensors were positioned, the control software held the specimen in place while the environmental chamber cooled the specimen to the desired test temperature. Specimens were soaked at the predetermined test temperature for a minimum of 30 minutes before the testing sequence was activated. Specimens were tested at quasistatic loading

rates using a fully automated servo-hydraulic materials test system. The testing sequence was comprised of a monotonic loading rate of 0.05 mm/s. Analog signals were generated from an instrumented load cell, and the nine LVDT sensors were digitized using a 14 bit A/D converter and stored in a microprocessor for further analysis.

4.0 RESULTS AND DISCUSSION

4.1 ASTM E-604 Test Results

Figures 4-11 represent the transition data generated for the eight specimen configurations tested. With the exception of the pressed-notch, side-grooved specimens, the data from lower shelf (brittle) to upper shelf (ductile) combined to generate typical transition curve morphologies. Visual examination of the fracture surfaces of the pressed-notch side-grooved specimens revealed significant amounts of out of plane fracture which would result in the significant scatter in absorbed impact energy observed for this specimen configuration. It can also be observed by comparing Figure 1 to Figure 5 and Figure 2 to Figure 6 that non side-grooved pressed-notch specimens produced transition curves which compare favourably with precracked non side-grooved specimens. Since the constraint conditions imposed at the tip of a deeply notched precracked non side-grooved specimen should simulate those imposed at the tip of a through thickness structural crack, this testing indicates that transition curves generated with ASTM E-604 specimens (pressed-notch) should accurately predict structural transition response.

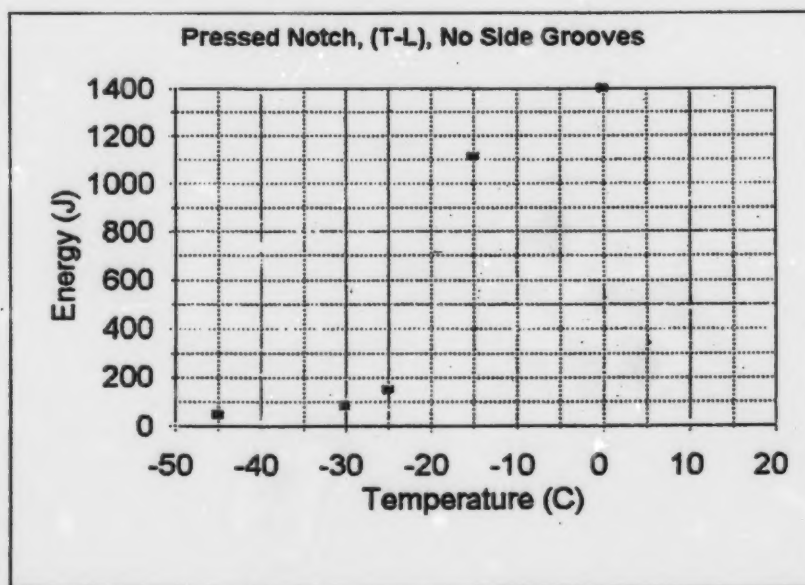


Figure 4 - Temperature transition curve for standard ASTM E-604 specimens. The notch was oriented in the T-L direction and the notch tip was pressed in accordance with ASTM E-604.

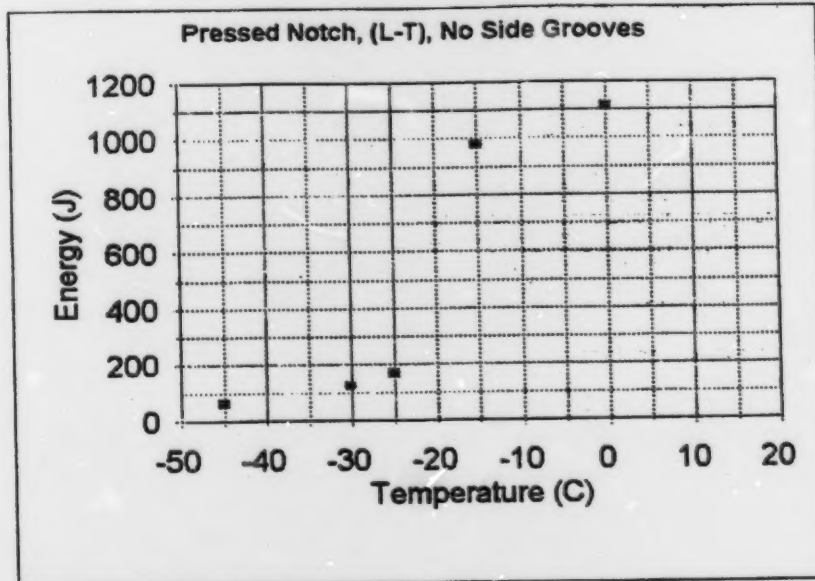


Figure 5 - Temperature transition data for standard ASTM E-604 specimens. The notch was oriented in the L-T direction and the notch tip was pressed in accordance with ASTM E-604.

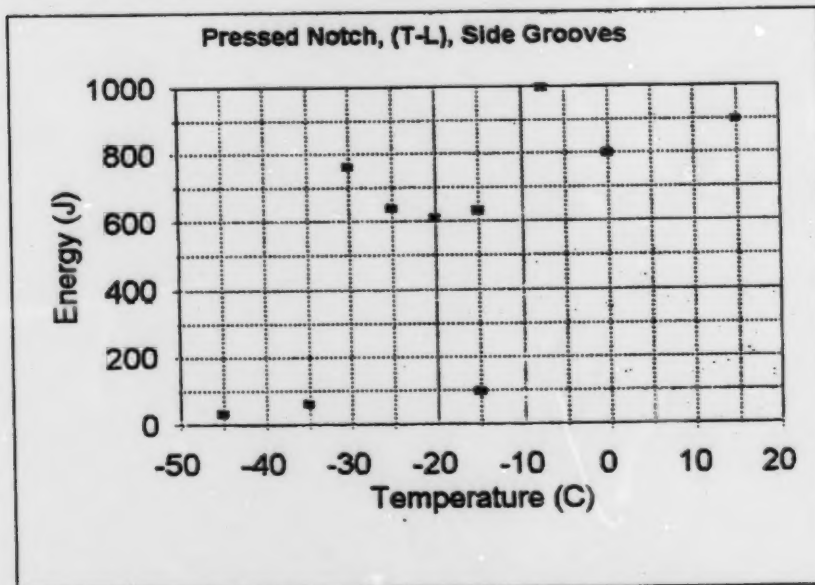


Figure 6- Temperature transition data for ASTM E-604 specimens with a 20 percent of the thickness side groove. The notch was oriented in the T-L direction and the notch tip was pressed in accordance with ASTM E-604.

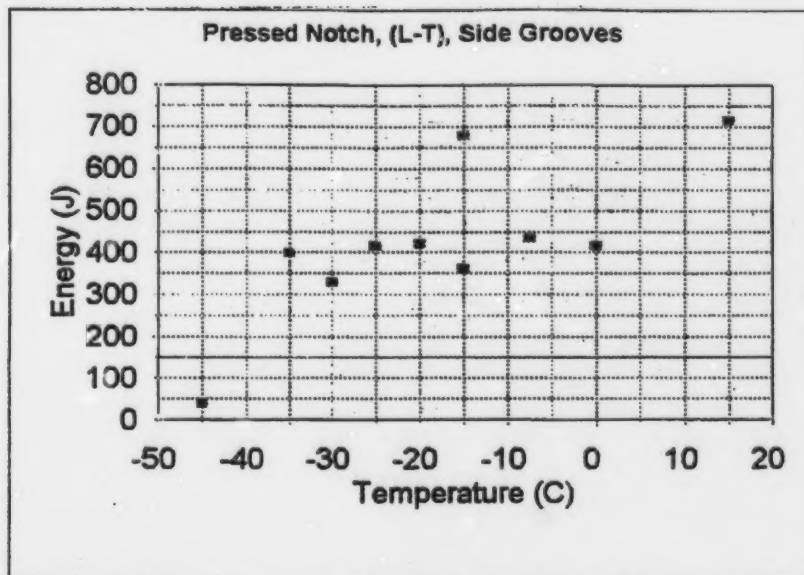


Figure 7 - Temperature transition data for ASTM E-604 specimens with a 20 percent of the thickness side groove. The notch was oriented in the L-T direction and the notch tip was pressed in accordance with ASTM E-604.

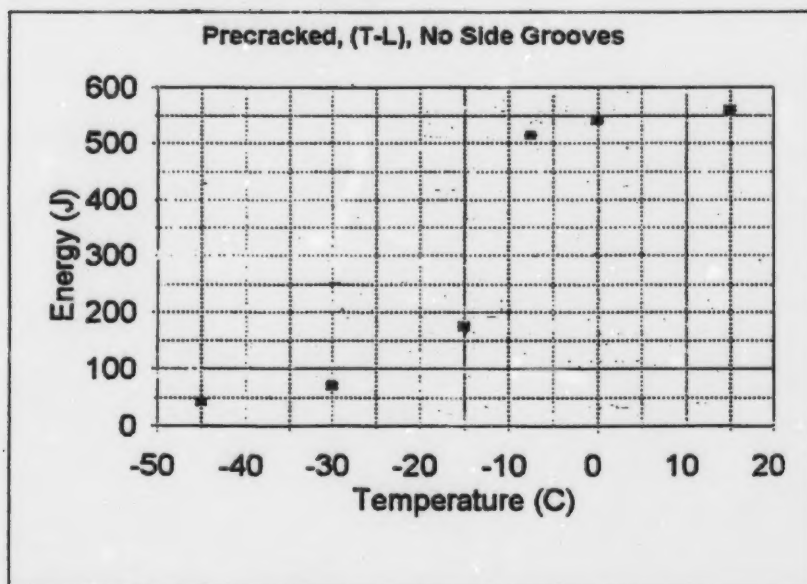


Figure 8 - Temperature transition data for ASTM E-604 specimens precracked to .54 a/W with the notch oriented in the T-L orientation.

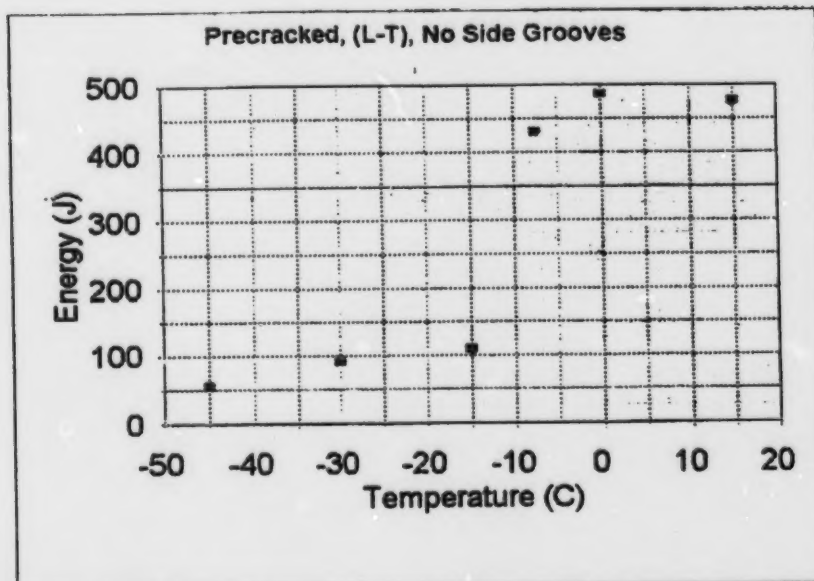


Figure 9 - Temperature transition data for ASTM E-604 specimens precracked to 0.54 a/W with the notch oriented in the L-T orientation.

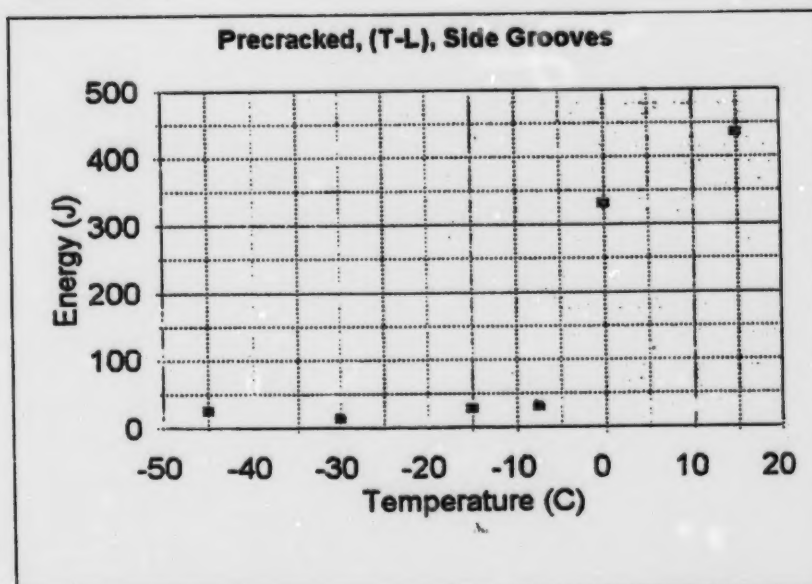


Figure 10 - Transition data for ASTM E-604 specimens side grooved to 20 percent of the specimen thickness and precracked to .54 a/W. The notch for these specimens was machined in the T-L orientation.

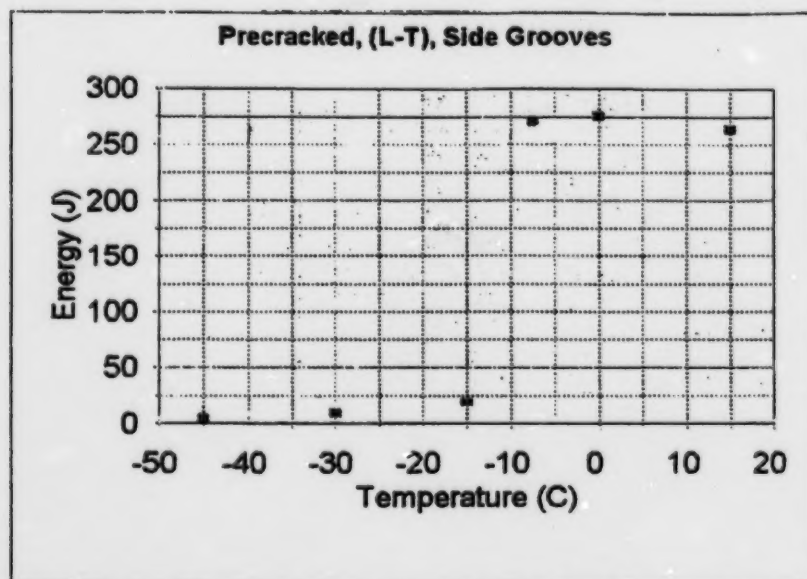


Figure 11 - Transition data for specimens side grooved to 20 percent of the specimen thickness and precracked to .54 a/W. The notch for these specimens was machined in the L-T orientation.

4.2 ASTM E-813 Test Results

Figures A.1 through A.11 (Appendix A) and Figures B.1 through B.10 (Appendix B) show graphical representations of the elastic and elastic-plastic analysis, respectively. Table 1 summarizes the results generated by these analyses. The load displacement records combined with the E-399 analysis generated for the plate and weldment materials indicate that the capacity of the specimens was insufficient to generate K controlled crack extension for all the specimens tested.

The elastic-plastic results indicate that the 350WT specimens with the notch orientation in the L-T direction (C54, C56) experience limit load tearing at both -30 °C and -50 °C. The fracture surfaces of these specimens revealed limited crack growth confined to the center region of the crack front. The 350WT T-L specimens (C512, C510) produced significant amounts of ductile crack extension at -30 °C and -50 °C. An examination of the validity criteria for both of these specimens indicate that only the crack front straightness criteria failed (these specimens produced triangular cracks). These specimens produced J_Q values within the J capacity of the specimens indicating J controlled crack extension.

Table 1 - Summary of E-399 and E-813 results for plate and weldment specimens tested

Specimen	Temp °C	KQ (MPa√m)	Validity	JQ (MPa.m)	Validity
C15	-30	55.72	No	70.51	No
C25	-30	56.77	No	237.70	No
C24	-50	72.57	No	280.28	No
C34	-30	81.41	No	198.57	No
C44	-30	61.74	No	**113.50	No
C45	-50	58.64	No	Plastic	No
C54	-30	56.14	No	Plastic	No
C55	-30	60.97	No	Plastic	No
C56	-50	59.01	No	Plastic	No
C512	-30	55.56	No	90.44	No
C510	-50	61.52	No	126.54	No

**** Initiated a brittle instability from a blunted crack.**

The 350WT weldment specimens from the 4 Aft plate section produced a brittle instability of the blunted crack at -30 °C (C44) and exhibited limited load tearing at -50 °C (C45). This variation, which counters the expected trend between toughness and temperature, is attributed to the inherent variability of the deposited weld material. The 350WT weldment specimen taken from plate section 1Aft (C34) generated a fracture surface where ductile crack extension is intermittently interrupted by "pop ins" caused by local brittle zones. This specimen produced crack growth within the J capacity of the specimen (like the 350WT T-L specimens, the crack front straightness criteria was not valid).

The A517 weldment specimens machined from plate section 2 Aft generated J controlled crack growth at both -30 °C (C25) and -50 °C (C24) (J_Q values are within the capacity of the specimen dimensions). At -30 °C "pop ins" attributed to local brittle zones were observed both in the load displacement record and the fracture surface. The fracture surface from the specimen tested at -50 °C revealed 100 percent ductile crack growth. The A517 weldment removed from plate section 3 Aft (C34) generated J controlled crack extension. Both the J-R curve and the fracture surface indicate the presence of a local brittle zone (the load displacement record does not show evidence of a "pop in").

4.3 Strain Energy Density Test Results

Figure 12 shows a typical load displacement record using the multi point deflection gauge developed for a tension specimen tested at 22 °C. In this case, gauge D1 (Figure 2) was used as the reference point to generate the relative displacements. Visual examination of the specimen subsequent to testing revealed that the specimen fractured at approximately D5 (midspan). The fracture surface was characterized by a flat plane strain region in the center of the specimen surrounded by oblique shear lips generated around the circumference of the fracture plane. The instrumented displacement data indicates that interval plastic deflection increases as the interval position moves toward the fracture plane of the specimen from both ends of the gauge length. If the intervals adjacent to position D5 (D4 and D6) are used to generate the stress-strain, the resulting relationship is given in Figure 13. The instrumented record indicates that the plastic stress-strain relationship is parabolic with an ultimate failure stress and strain of 720 MPa and 0.8 mm/mm (80%), respectively. The stress-strain couplet generated using the visually measured final necked diameter and the visually measured displacement between the scribed lines D4 and D6 are 930 MPa and 1.09 mm/mm (109%), respectively. The difference in stress determined from the instrumented load displacement traces and the instrumented load combined with the visually measured cross sectional area is due to the interval averaging effect of determining stress from instrumented strain displacements of a specimen experiencing necking. Over the instrumented interval used to determine the strain (D4-D6), the visually measured diameter of the specimen varies in diameter from 14.16 mm @ D4 to 12.03 mm @ D5 to 14.26 mm @ D6. The method for determining the instantaneous cross sectional area from instrumented displacement data assumes that the gauge length contained between D4 and D6 maintains constant volume in the plastic range of the test. Thus, any variation in the specimen diameter along the gauge length used (in this case D4 and D6) is averaged (treated as if the gauge is deforming uniformly). If the visually measured points between D4 and D6 are averaged, then the calculated failure stress is approximately 770 MPa which approximates the stress calculated from the instrumented deflection record between D4 and D6. Thus, this comparison provides a check on the accuracy of the instrumented deflections recorded.

The confirmation of accuracy of the deflection measurements through the previously described procedure contradicts the visually measured longitudinal displacements measured between the scribed lines between D4 and D6 (measured strain is 20% higher). The key to understanding this discrepancy lies in understanding the development of the fracture plane during the final stages of the test. In specimens which have sufficient through thickness dimensions such that a significant portion of the interior of the fracture plain is in plane strain, the initiation of the fracture event will occur in the interior of the specimen through void coalescence. The interior fracture plane will continue to propagate towards the exterior surface. The exterior surface of the specimen (the plane stress region of the specimen) will continue to sustain the deflections imposed on the specimen. If the specimen ductile load instability corresponds to the initiation of the interior fracture plane, then discrepancies between strain generated from instrument displacement records and visually measured surface strains will exist. An analogous set of events is the trailing of the shear lip behind the propagating plain strain portion of an advancing crack in a three-point-

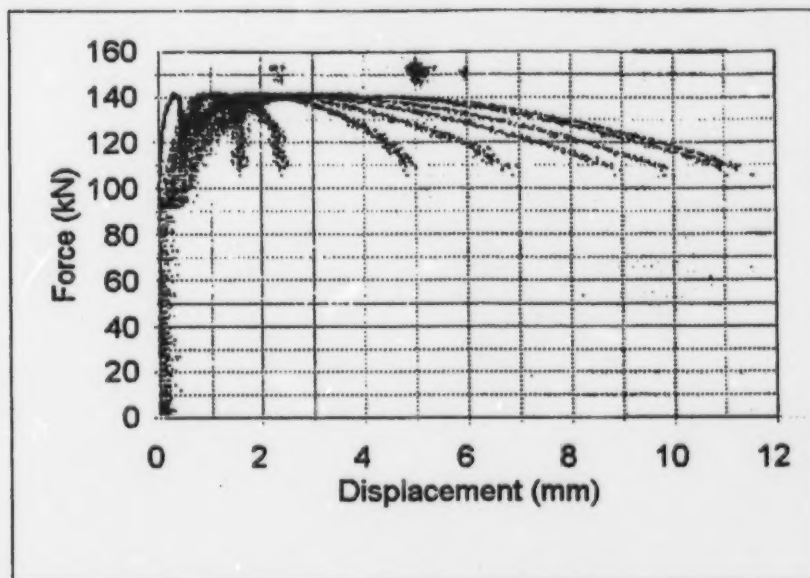


Figure 12 - Typical load-displacement curves generated from multi-point extensometer.



Figure 13 - Calculated stress-strain relationship for tension specimen tested at 22°C.

bend specimen. Thus, strains monitored on the surface of the specimen adjacent to the fracture plane will provide an accurate global response of the specimens under predominately plane stress conditions only.

Figures 14 and 15 show the stress strain relationships for the 38WT specimens tested at -20 °C and -40 °C, respectively. While the failure stress remains relatively unchanged, the total instrumented strain at failure has decreased from 80% @ 22 °C to approximately 65% @ -20 °C and -40 °C. If the area under each stress strain curve is considered to be correlated to the critical strain energy density, then these values are calculated as 4.8×10^8 N-m/m³, 3.9×10^8 N-m/m³ and 3.9×10^8 N-m/m³ for 22 °C, -20 °C and -40 °C, respectively.

The stress-strain plots and cumulative strain energies calculated for the three specimens indicate a decrease in toughness as the temperature decreases from 22 °C to -20 °C. Comparing the stress-strain relationships generated from the specimens tested at -20 °C and -40 °C indicates an independence of stress-strain properties of test temperature over this temperature interval. A possible explanation for this observed independence is that the fully plastic specimen gauge length is generating heat owing to the deformation processes. The heat generated from plasticity is generated throughout the interior of the specimen. The cooling process from the environmental chamber relies on the conductive properties of the material acting through the surface of the specimen in an attempt to maintain the test temperature across the specimen gauge diameter. Thus, if the temperature at the core of the specimen were increased owing to plastically generated heat, a certain interval time would be required to lower the core back to test temperature.

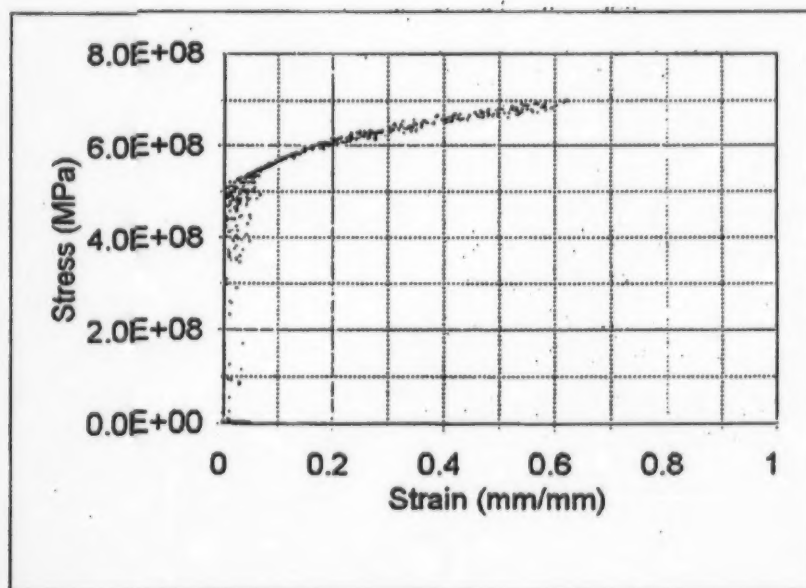


Figure 14 - Calculated stress-strain relationship for tension specimen tested at -20°C.

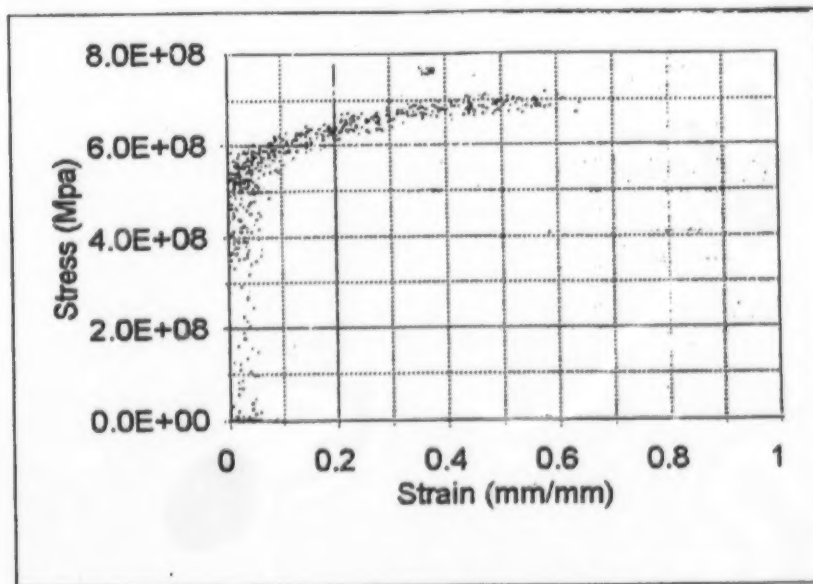


Figure 15 - Calculated stress-strain relationship for tension specimen tested at -40°C.

5.0 CONCLUSIONS

Several inferences can be generated as a result of the experimental program executed during this study:

- 1) The temperature shift between transition curves generated using ASTM E-604 pressed-notch specimens and precracked specimens is minimal. The inclusion of side grooves to either pressed notch or precracked specimens produces varying degrees of out of plane crack propagation which is visually apparent on the resulting fracture surface.
- 2) Test results from fracture specimens machined from structural steel and plate cutouts removed from HMCS Calgary can be summarized as follows.
 - 350 WT plate L-T orientation - Limit load tearing at -30°C and -50°C
 - 350 WT plate T-L orientation - J controlled ductile crack extension at -30°C and -50°C
 - 350WT weldment - inconsistent results (brittle initiation at -30°C and limit load tearing at -50 °C)
 - A517 weldment - J controlled crack extensions with "pop ins" at -30°C and -50°C
- 3) A customized displacement sensor suite for measuring linear differential displacement at multiple sites along the gauge length of a uniaxial tension specimen has been developed. Predicted average cross sectional area from the displacement data indicated that the sensor suite provides accurate displacement data.
- 4) Stress-strain relationships generated for CSA G40.21 38WT indicate that the strain energy density capacity of the material decreases as the initial specimen temperature is lowered from 22 °C to -20 °C. Further study is required to ascertain whether internal heating of the specimen owing to the gross plastic deformation of the specimen gauge influences the strain energy density toughness levels observed.

6.0 REFERENCES

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APPENDIX A - Elastic Test Results ASTM E-399

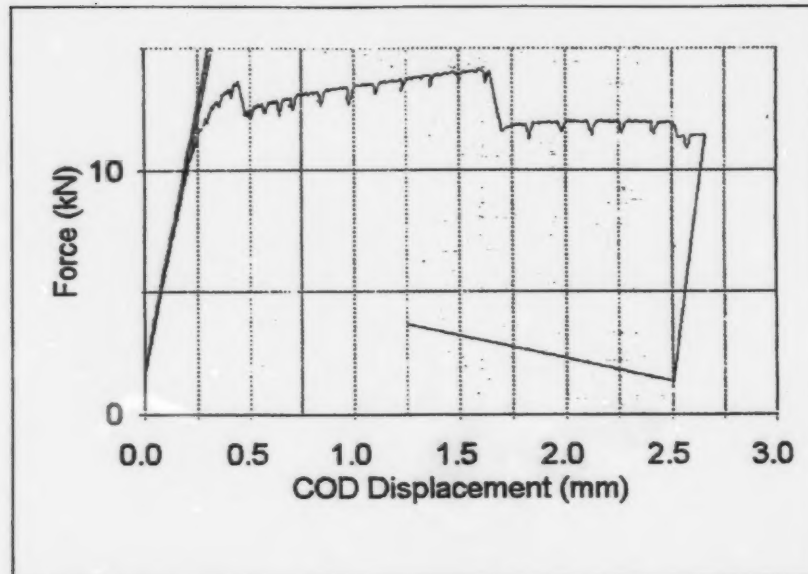


Figure A.1 - ASTM E399 test results for 1Aft 350WT weldment C15 tested at -30 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-206
Material Type: Calgary_350WT_C15
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.65 mm
Specimen Thickness: 9.76 mm
Specimen Span: 164.50 mm
Initial Specimen Compliance 44.69 mm/kN
Initial Crack Length Readings 20.59 mm 20.89 mm 20.52 mm
Average Crack Length 20.67 mm 0.508405 a/W Valid

Fracture Toughness K_{Ic} : 55.72 Mpa $\sqrt{\text{m}}$

Validation Criteria

P_{max}/P_Q 13.94/9.91 1.41 Invalid
Through Thickness Constraint Invalid $9.76 < 25.345860$
Remaining Ligament Constraint Invalid $19.98 < 25.345860$

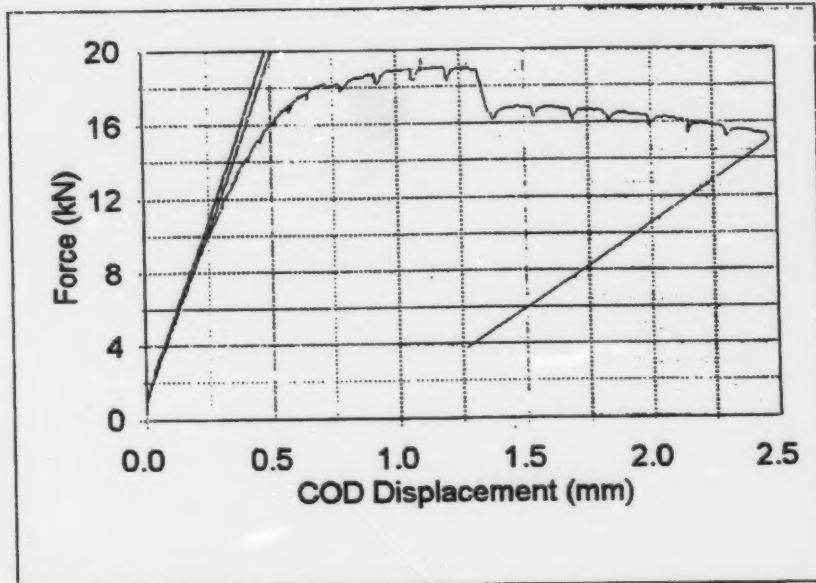


Figure A.2 - ASTM E399 test results for 2Aft A517 weldment C25 tested at -30 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-203
 Material Type: Calgary_350WT_C25
 Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.70 mm
 Specimen Thickness: 9.34 mm
 Specimen Span: 164.50 mm
 Initial Specimen Compliance 39.50 mm/kN
 Initial Crack Length Readings 21.85 mm 22.43 mm 21.61 mm
 Average Crack Length 21.96 mm 0.539640 a/W Valid

Fracture Toughness K_I : 56.77 Mpa $\sqrt{\text{m}}$

Validation Criteria

P_{max} 18.81 P_Q 8.73 P_{max}/P_Q 2.15 Invalid
 Through Thickness Constraint Valid 9.34 < 12.575
 Remaining Ligament Constraint Invalid 18.74 < 12.575

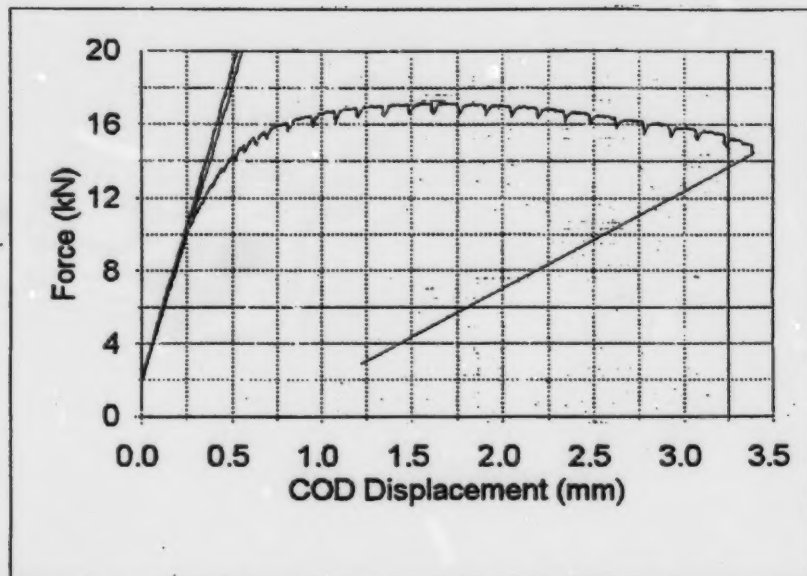


Figure A.3 - ASTM E399 test results for 2Aft A517 weldment C24 tested at -50 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-208

Material Type: Calgary_350WT_C24

Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.60 mm

Specimen Thickness: 9.31 mm

Specimen Span: 164.50 mm

Initial Specimen Compliance 34.77 mm/kN

Initial Crack Length Readings 22.29 mm 22.82 mm 22.09 mm

Average Crack Length 22.40 mm 0.551724 a/W Valid

Fracture Toughness K_q: 72.57 Mpa sqrt(m)

Validation Criteria

P_{max} 16.99 P_q 10.63 P_{max}/P_q 1.60 Invalid

Through Thickness Constraint Invalid 9.31 < 20.57

Remaining Ligament Constraint Invalid 18.20 < 20.57

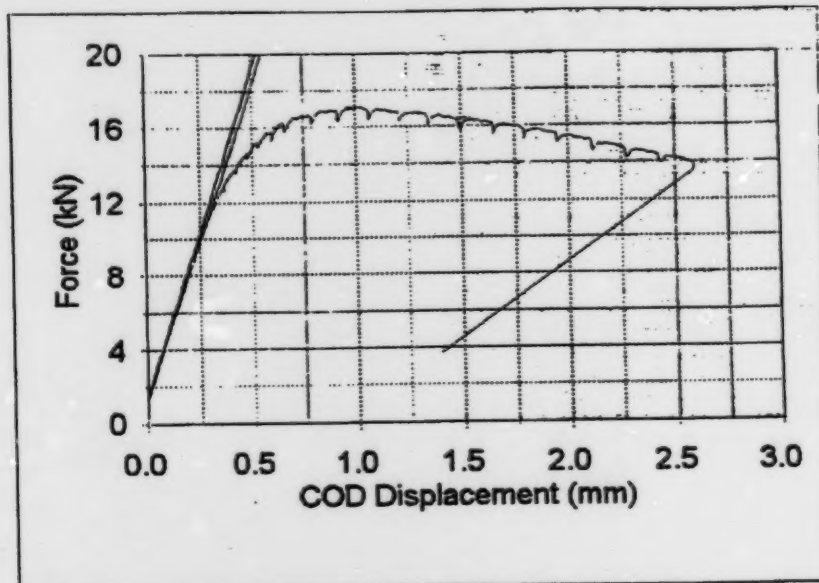


Figure A.4 - ASTM E399 test results for 3Aft A517 weldment C34 tested at -30 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-202
 Material Type: Calgary_350WT_C34
 Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.59 mm
 Specimen Thickness: 9.15 mm
 Specimen Span: 164.50 mm
 Initial Specimen Compliance 35.89 mm/kN
 Initial Crack Length Readings 22.31 mm 22.43 mm 22.10 mm
 Average Crack Length 22.28 mm 0.548904 a/W Valid

Fracture Toughness Kq: 81.41 Mpa sqrt(m)

Validation Criteria

Pmax 16.90 Pq 11.83 Pmax/Pq 1.43 Invalid
 Through Thickness Constraint Invalid 9.15 < 24.56
 Remaining Ligament Constraint Invalid 18.31 < 24.56

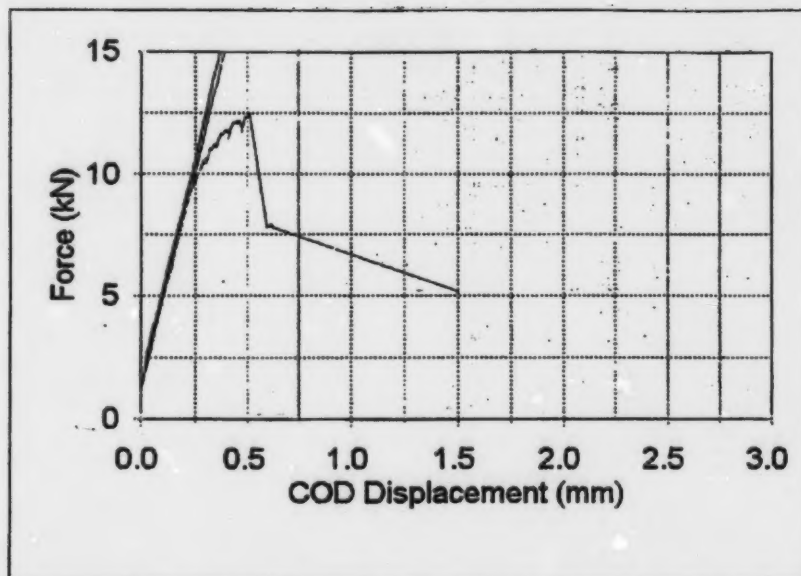


Figure A.5 - ASTM E399 test results for 4Aft 350WT weldment C44 tested at -30 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-207

Material Type: Calgary_350WT_C44

Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.70 mm

Specimen Thickness: 9.50 mm

Specimen Span: 164.50 mm

Initial Specimen Compliance 37.65 mm/kN

Initial Crack Length Readings 22.44 mm 22.10 mm 21.21 mm

Average Crack Length 21.92 mm 0.538493 a/W Valid

Fracture Toughness K_{Ic} : 61.74 Mpa sqrt(m)

Validation Criteria

P_{max}/P_Q 12.12 P_Q 9.69 P_{max}/P_Q 1.25 Invalid

Through Thickness Constraint Invalid 9.50 < 31.117056

Remaining Ligament Constraint Invalid 18.78 < 31.117056

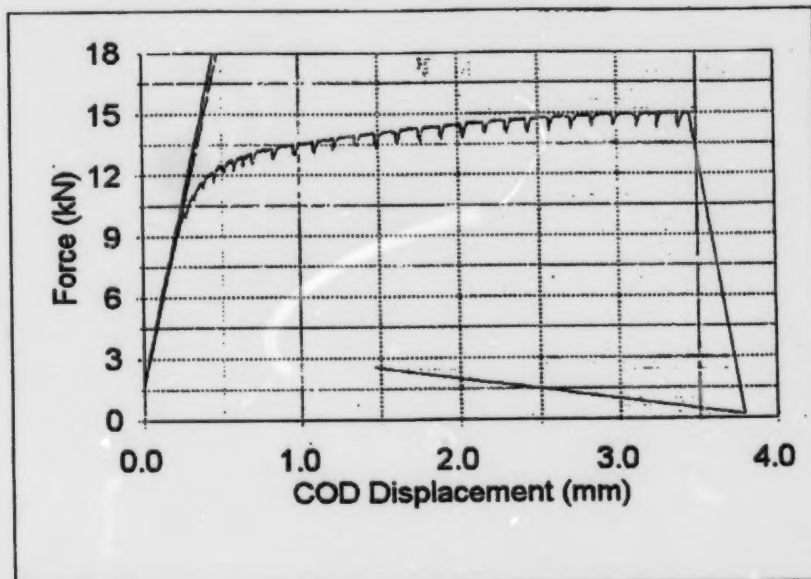


Figure A.6 - ASTM E399 test results for 4Aft 350WT weldment C45 tested at -50 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-209
 Material Type: Calgary_350WT_C45
 Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.73 mm
 Specimen Thickness: 9.43 mm
 Specimen Span: 164.50 mm
 Initial Specimen Compliance 36.54 mm/kN
 Initial Crack Length Readings 21.80 mm 22.10 mm 21.81 mm
 Average Crack Length 21.90 mm 0.537769 a/W Valid

Fracture Toughness Kq: 58.64 Mpa sqrt(m)

Validation Criteria

Pmax 14.84 Pq 9.17 Pmax/Pq 1.62 Invalid
 Through Thickness Constraint Invalid 9.43 < 28.073780
 Remaining Ligament Constraint Invalid 18.83 < 28.073780

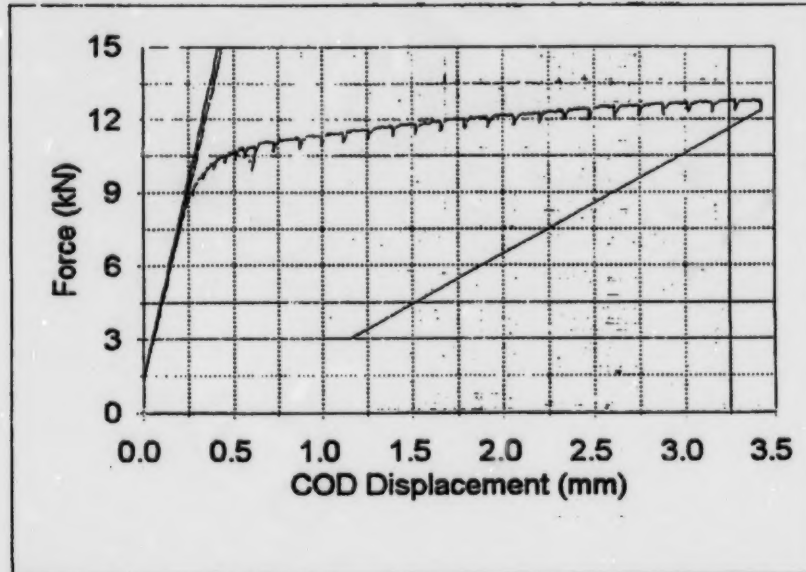


Figure A.7 - ASTM E399 test results for 5Aft 350WT Plate C54 tested at -30 °C (L-T orientation).

TEST RESULTS

Specimen Identification: Specimen-8005-201
 Material Type: Calgary_350WT_C54
 Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.74 mm
 Specimen Thickness: 9.31 mm
 Specimen Span: 164.50 mm
 Initial Specimen Compliance 33.59 mm/kN
 Initial Crack Length Readings 22.80 mm 22.70 mm 22.30 mm
 Average Crack Length 22.60 mm 0.554737 a/W Valid

Fracture Toughness K_{Ic} : 56.14 Mpa sqrt(m)

Validation Criteria

P_{max}/P_Q 12.61 P_Q 8.18 P_{max}/P_Q 1.54 Invalid
 Through Thickness Constraint Invalid 9.31 < 25.729359
 Remaining Ligament Constraint Invalid 18.14 < 25.729359

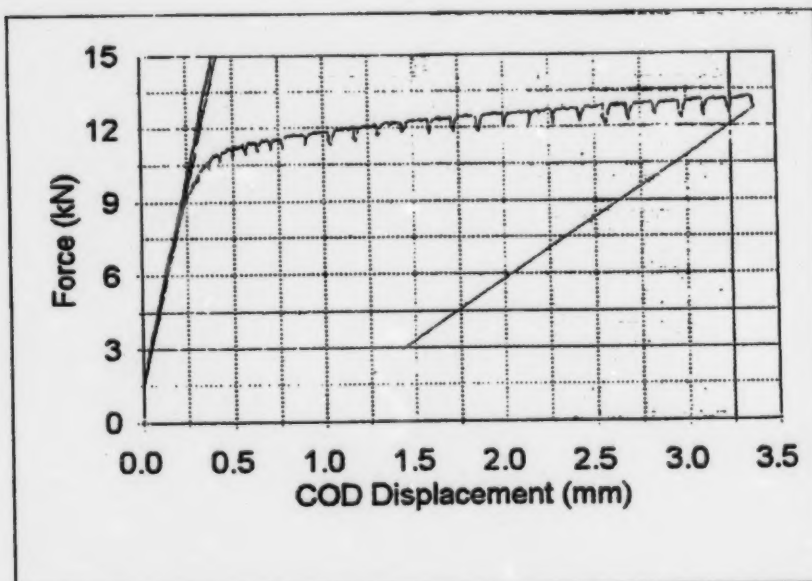


Figure A.8 - ASTM E399 test results for 5Aft 350WT Plate C55 tested at -30 °C (L-T orientation).

TEST RESULTS

Specimen Identification: Specimen-8005-204

Material Type: Calgary_350WT_C55

Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.70 mm

Specimen Thickness: 9.22 mm

Specimen Span: 164.50 mm

Initial Specimen Compliance 34.76 mm/kN

Initial Crack Length Readings 21.98 mm 22.34 mm 22.21 mm

Average Crack Length 22.18 mm 0.544881 a/W Valid

Fracture Toughness K_Q : 60.97 Mpa sqrt(m)

Validation Criteria

P_{max} 12.98 P_Q 9.09 P_{max}/P_Q 1.43 Invalid

Through Thickness Constraint Invalid $9.22 < 30.345297$

Remaining Ligament Constraint Invalid $18.52 < 30.345297$

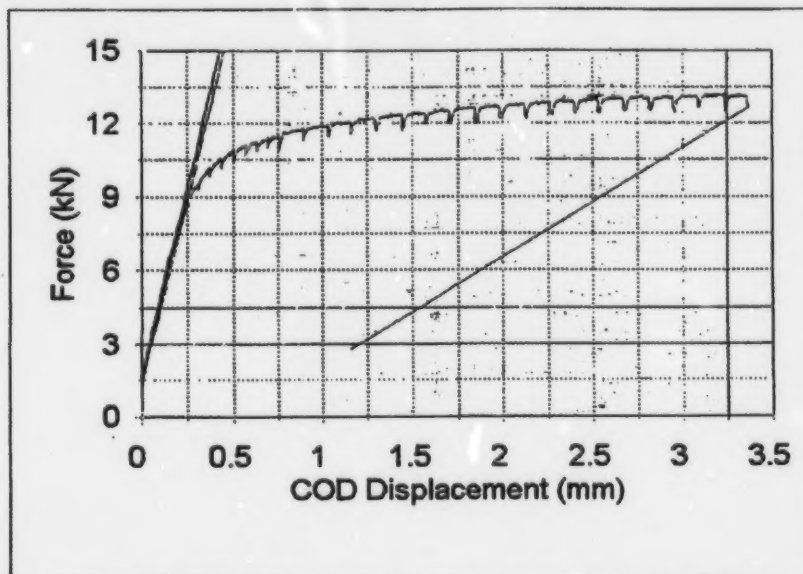


Figure A.9 - ASTM E399 test results for 5Aft 350WT plate C56 tested at -50 °C (L-T orientation).

TEST RESULTS

Specimen Identification: Specimen-8005-210

Material Type: Calgary_350WT_C56

Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.64 mm

Specimen Thickness: 9.26 mm

Specimen Span: 164.50 mm

Initial Specimen Compliance 32.10 mm/kN

Initial Crack Length Readings 23.33 mm 22.66 mm 21.27 mm

Average Crack Length 22.42 mm 0.551673 a/W Valid

Fracture Toughness K_{Ic} : 59.01 Mpa sqrt(m)

Validation Criteria

P_{max}/P_Q 13.00 P_Q 8.61 P_{max}/P_Q 1.51 Invalid

Through Thickness Constraint Invalid 9.26 < 28.426149

Remaining Ligament Constraint Invalid 18.22 < 28.426149

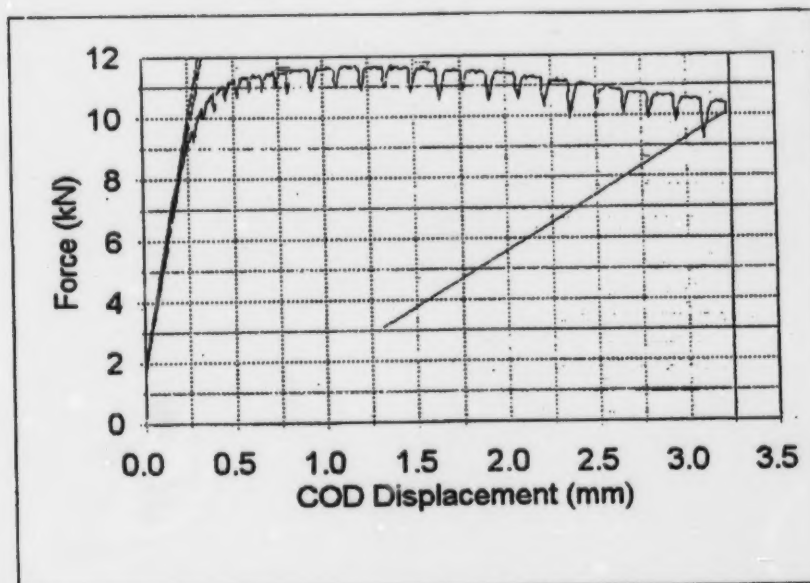


Figure A.10 - ASTM E399 test results for 5Aft 350WT plate C512 tested at -30 °C (T-L orientation).

TEST RESULTS

Specimen Identification: Specimen-8005-205
 Material Type: Calgary_350WT_C512
 Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.77 mm
 Specimen Thickness: 9.23 mm
 Specimen Span: 164.50 mm
 Initial Specimen Compliance 33.62 mm/kN
 Initial Crack Length Readings 21.45 mm 22.47 mm 22.43 mm
 Average Crack Length 22.12 mm 0.542474 a/W Valid

Fracture Toughness K_{Ic} : 55.56 Mpa $\sqrt{\text{m}}$

Validation Criteria

P_{max}/P_Q 11.53 P_Q 8.38 P_{max}/P_Q 1.38 Invalid
 Through Thickness Constraint Invalid $9.23 < 25.197193$
 Remaining Ligament Constraint Invalid $18.65 < 25.197193$

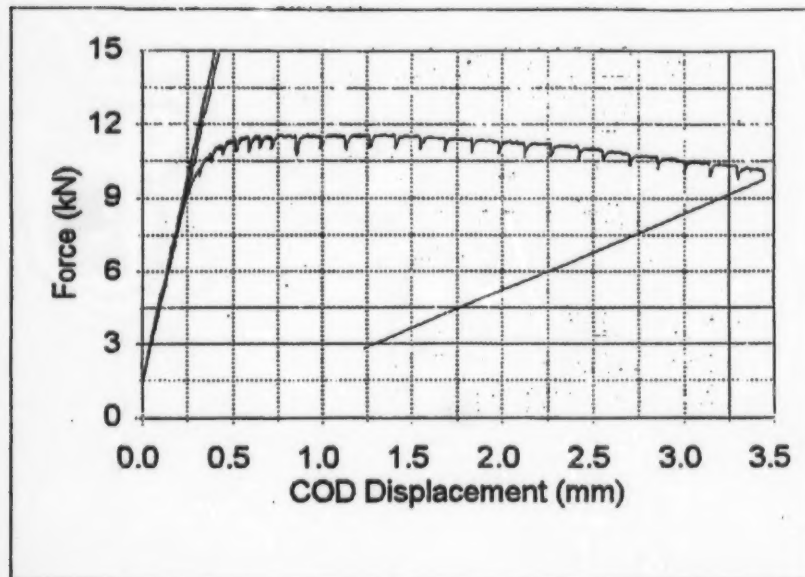


Figure A.11 - ASTM E399 test results for 5Aft 350WT plate C510 tested at -50 °C (T-L orientation).

TEST RESULTS

Specimen Identification: Specimen-8005-211
 Material Type: Calgary_350WT_C510
 Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.66 mm
 Specimen Thickness: 9.26 mm
 Specimen Span: 164.50 mm
 Initial Specimen Compliance 34.49 mm/kN
 Initial Crack Length Readings 21.77 mm 22.19 mm 21.94 mm
 Average Crack Length 21.97 mm 0.540253 a/W Valid

Fracture Toughness K_{Ic} : 61.52 Mpa sqrt(m)

Validation Criteria

P_{max}/P_Q 11.42 P_Q 9.34 P_{max}/P_Q 1.22 Invalid
 Through Thickness Constraint Invalid 9.26 < 30.892437
 Remaining Ligament Constraint Invalid 18.69 < 30.892437

Appendix B - Elastic-Plastic Test Results ASTM E-813

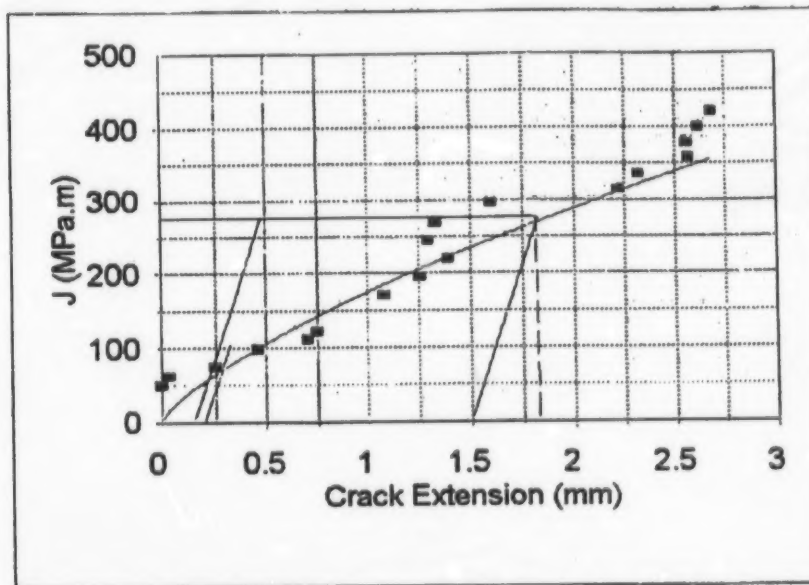


Figure B.1 - ASTM E813 test results for 1Aft 350WT weldment C15 tested at -30 °C.

Provisional J_q (kJ/m²) = 70.51

Through thickness constraint valid ($B=9.76$) > 4.15

Remaining Ligament constraint valid ($b_i=19.93$) > 4.15

dJ/da (180.32) is less than yield (425.00) (valid)

Fatigue precrack straightness valid 20.72 (mm)

Crack extension straightness invalid 25.19 (mm)

Compliance accuracy measurement valid

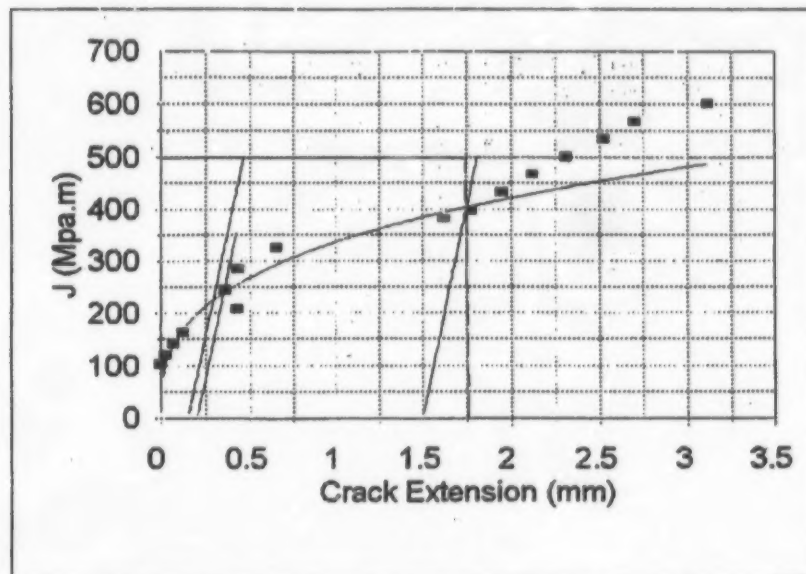


Figure B.2 - ASTM E813 test results for 2Aft A517 weldment C25 tested at -30 °C.

Provisional J_q (kJ/m²) = 237.70

Through thickness constraint valid ($B=9.34$) > 7.43

Remaining Ligament constraint valid ($b_i=18.65$) > 7.43

dJ/da (225.29) is less than yield (800.00) (valid)

Fatigue precrack straightness valid 22.05 (mm)

Crack extension straightness invalid 25.44 (mm)

Compliance accuracy measurement valid

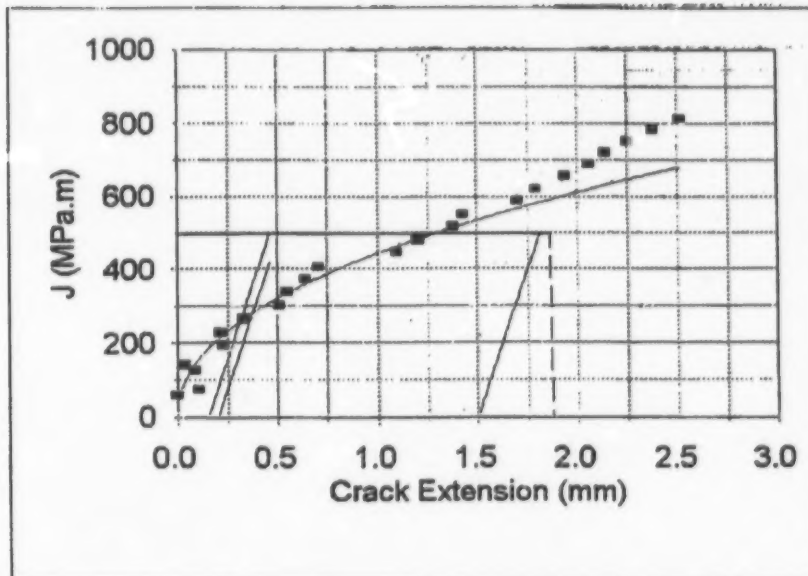


Figure B.3 - ASTM E813 test results for 2Aft A517 weldment C24 tested at -50 °C.

Provisional J_q (kJ/m²) = 280.28

Through thickness constraint valid ($B=9.31$) > 8.76

Remaining Ligament constraint valid ($b_i=18.21$) > 8.76

dJ/da (349.85) is less than yield (800.00) (valid)

Fatigue precrack straightness invalid 22.39 (mm)

Crack extension straightness invalid 25.84 (mm)

Compliance accuracy measurement valid

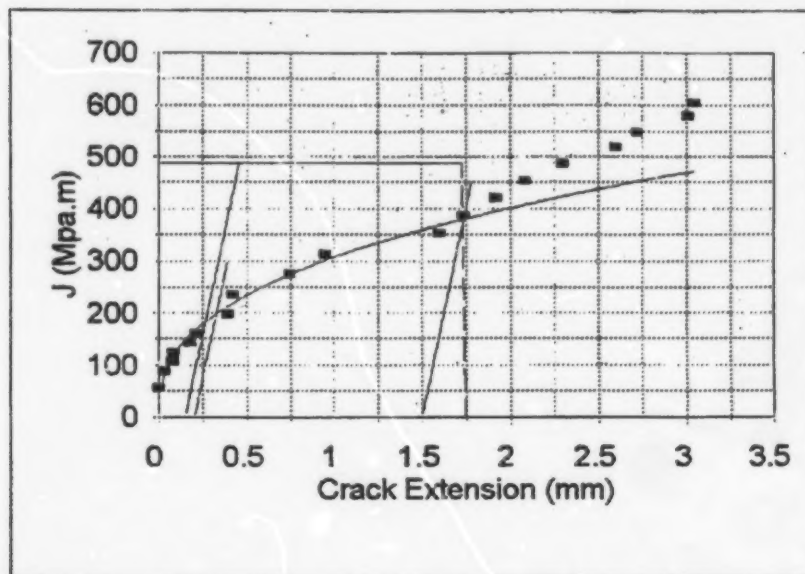


Figure B.4 - ASTM E813 test results for 3Aft A517 weldment C34 tested at -30 °C.

Provisional J_q (kJ/m²) = 198.57

Through thickness constraint valid ($B=9.15$) > 6.21

Remaining Ligament constraint valid ($b_i=18.32$) > 6.21

dJ/da (237.94) is less than yield (800.00) (valid)

Fatigue precrack straightness invalid 22.27 (mm)

Crack extension straightness invalid 25.74 (mm)

Compliance accuracy measurement valid

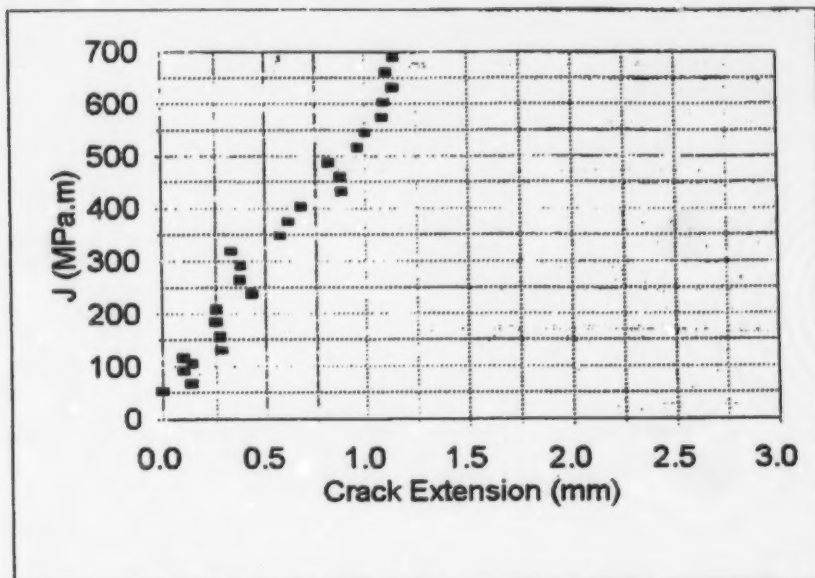


Figure B.5 - ASTM E813 test results for 4Aft 350WT weldment C45 tested at -50 °C.

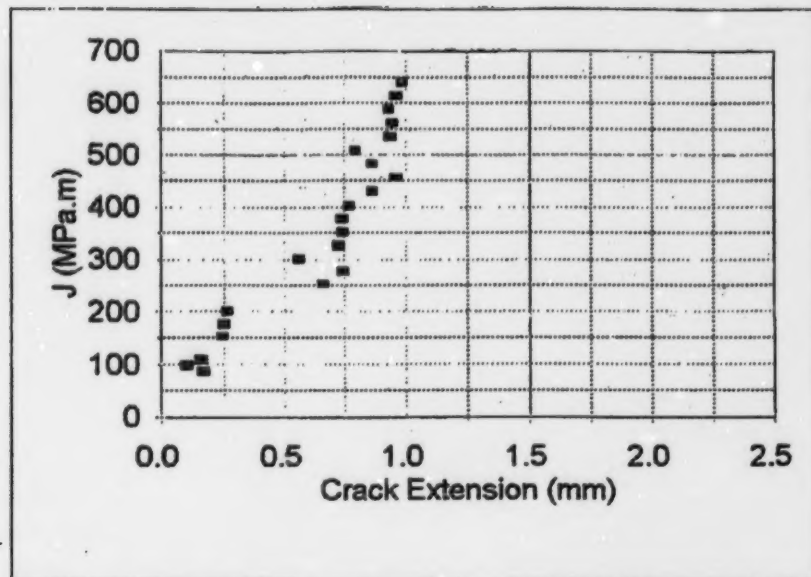


Figure B.6 - ASTM E813 test results for 5Aft 350WT plate C54 tested at -30 °C, (L-T orientation).

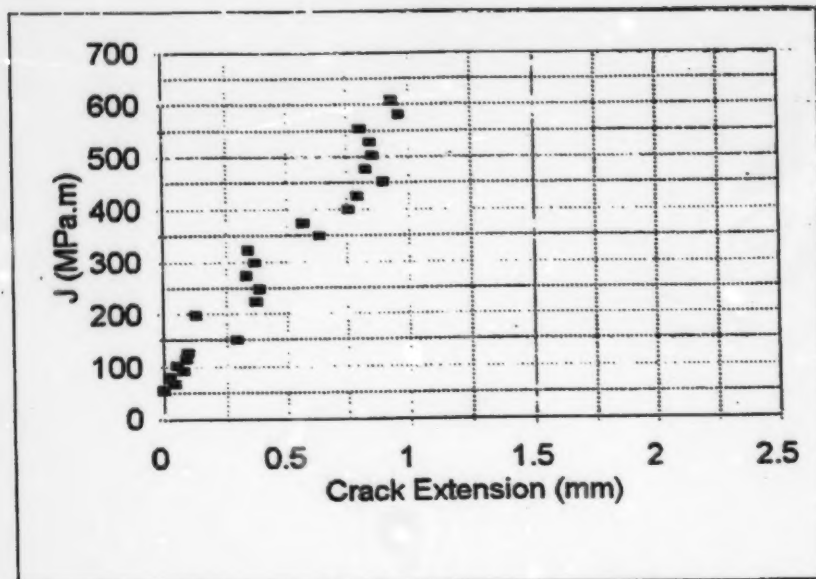


Figure B.7 - ASTM E813 test results for 5Aft 350WT plate C55 tested at -30 °C (L-T orientation).

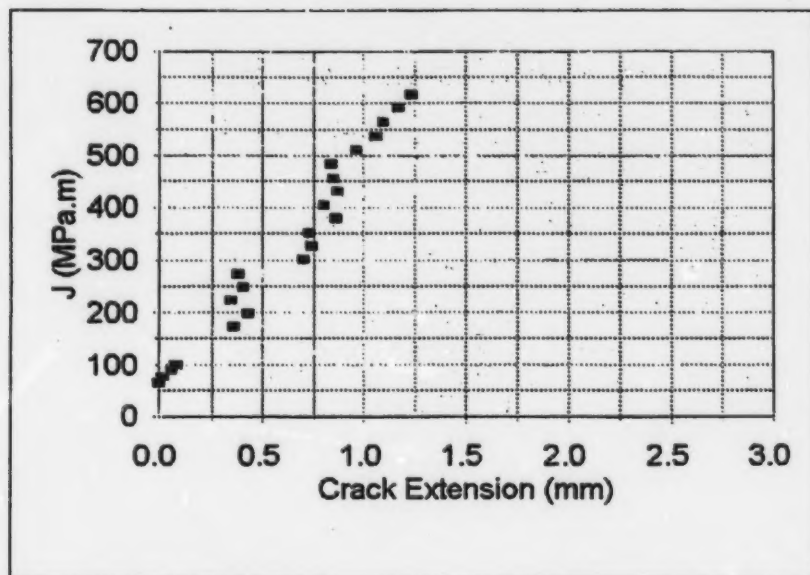


Figure B.8 - ASTM E813 test results for 5Aft 350WT plate C56 tested at -50 °C (L-T orientation).

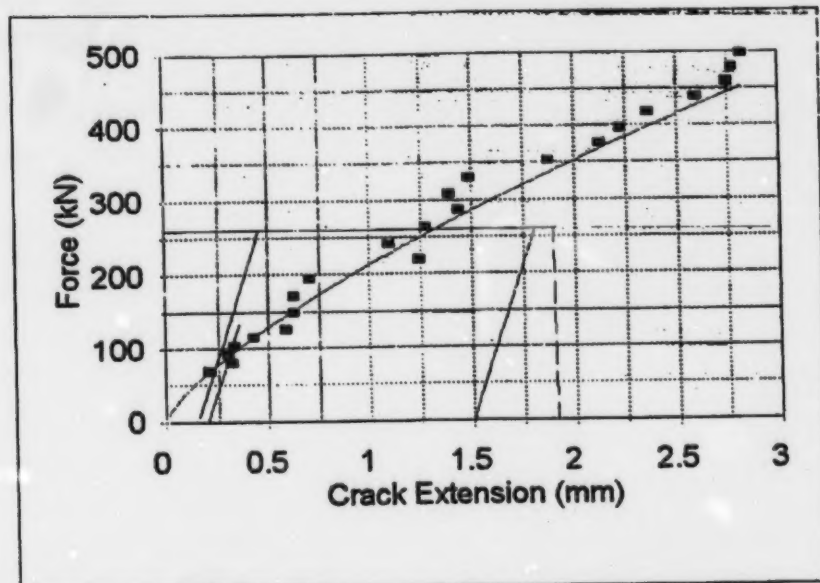


Figure B.9- ASTM E813 test results for 5Aft 350WT plate C512 tested at -30 °C, (T-L orientation).

Provisional J_q (kJ/m²) = 90.44

Through thickness constraint valid ($B=9.23$) > 5.32

Remaining Ligament constraint valid ($b_i=18.61$) > 5.32

dJ/da (214.59) is less than yield (425.00) (valid)

Fatigue precrack straightness invalid 22.16 (mm)

Crack extension straightness invalid 25.27 (mm)

Compliance accuracy measurement valid

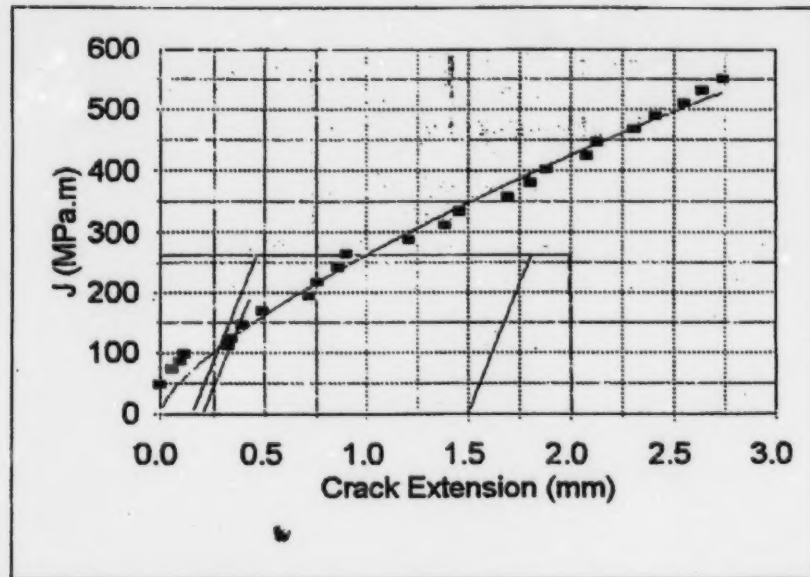


Figure B.10 - ASTM E813 test results for 5Aft 350WT plate C510 tested at -50 °C, (T-L orientation).

Provisional J_q (kJ/m²) = 126.54

Through thickness constraint valid ($B=9.26$) > 7.44

Remaining Ligament constraint valid ($b_i=18.50$) > 7.44

dJ/da (252.53) is less than yield (425.00) (valid)

Fatigue precrack straightness invalid 22.16 (mm)

Crack extension straightness invalid 25.27 (mm)

Compliance accuracy measurement valid

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SECURITY CLASSIFICATION OF FORM
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Accurate characterization of mechanical materials properties is integral to the development of marine platform designs which will exhibit acceptable levels of damage tolerance under extreme service conditions. A study has been performed to evaluate several laboratory test procedures for the characterization of fracture toughness in the ductile to brittle transition region. Test procedures evaluated include ASTM E-604, ASTM E-813, and strain energy density generated from uniaxial tension specimens. Marine structural steels and weldments used in the evaluation include CSA G40.21 350WT, CSA G40.21 38WT, and ASTM A-517.

A comparison of transition curves generated from pressed-notch ASTM E-604 specimens and fatigue precracked specimens indicates that the pressed-notch specimen geometry provides an acceptable approximation of structural transition. The addition of side grooves to E-604 specimens produced out of plane crack propagation resulting in significant scatter in the transition curve results.

Elastic and elastic-plastic fracture toughness tests conducted on 350WT plate specimens revealed limit load tearing in the L-T crack plane orientation and J-controlled crack extension in the T-L orientations. CSA G40.21 350WT weldments tested generated inconsistent results ranging from initiation of a brittle instability at -30°C to limit load tearing at -50°C. ASTM A-517 welds generally exhibited J-controlled crack extensions with "pop-ins" evident in the load-displacement records.

A customized uniaxial tension extensometer was developed for tracking deflections at multiple points along the gauge of a tension specimen. Accuracy of the extensometer was verified through the prediction of the average cross sectional area of the specimen over the minimum interval between measurement points adjacent to the fracture plane. The test results indicate a decrease in the strain energy density capacity of CSA G40.21 38WT as the temperature is lowered from 22°C to -20°C.

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Dynamic tear
Strain energy density
Tensile test
Extensometer
ASTM E 604
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